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ASSESSMENT OF THE CLIMATE CHANGE IMPACTS ON THE WATER RESOURCES OF THE LUNI REGION, INDIA

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ABSTRACT

Climate change is expected to have a strong impact on water resources at the local, regional and global scales. In this study, the impact of climate change on the hydro-climatology of the Luni region, India, is investigated by comparing statistics of current and projected future fluxes resulting from three representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5). The use of different scenarios allows for the estimation of uncertainty of future impacts. The projections are based on the CORDEX-South Asia framework and are bias-corrected using the DBS method before being entered into the HYPE (HYdrological Predictions for the Environment) hydrological model to generate predictions of runoff, evapotranspiration, soil moisture deficit, and applied irrigation water to soil. Overall, the high uncertainty in the climate projections is propagated in the impact model, and as a result the spatiotemporal distribution of change is subject to the climate change scenario. In general, for all scenarios, results show a -20 to +20% change in the long-term average precipitation and evapotranspiration, whereas more pronounced impacts are expected for runoff (-40 to +40% change). Climate change can also affect other hydro-climatic components, however, at a lower impact. Finally, the flow dynamics in the Luni River are substantially affected in terms of shape and magnitude.

Keywords: Hydrological modelling, HYPE, climate change impacts, water resources, Luni river

1. Introduction

India is expected to be seriously affected by the impacts of climate change since the national economy relies on agriculture and natural resources, i.e., water (GoI, 2004). The region already faces water stresses due to increase in population, urbanisation, and increasing demands in the agriculture, industrial and hydropower sectors. Climate change is expected to further aggravate water shortage (Gosain *et al.*, 2011; Raje *et al.*, 2014). The State of Rajasthan, in the western part of the country, is severely deficient in water resources, whereas changes are being already experienced in its climate indicating an increase in annual mean surface temperature of 2-4 °C (GoR, 2011). The mean annual rainfall is expected to slightly decrease, but the extreme rainfall is expected to increase in frequency and intensity. It is, therefore, likely that Rajasthan will experience water shortage. In addition, the Government of Rajasthan acknowledged that not many climate modelling analysis studies are available for the region, and urged the need to develop a solid basis for future water management and adaptation, as well as formulation of integrated river basin development plans under future climatic

conditions.

Assessment of future climate change impacts on water resources commonly involves climate variables (i.e., precipitation, temperature) from global climate models (GCMs) in combination with hydrological models (Pechlivanidis *et al.*, 2011). GCMs demonstrate significant skill at the continental and hemispheric spatial scales and incorporate a large proportion of the complexity of the global system; however, they are inherently unable to represent local basin-scale features and dynamics (Fowler *et al.*, 2007). To narrow the gap between GCMs' ability and hydrological needs, regional climate models (RCMs) have been developed to generate high-resolution meteorological inputs. RCMs transfer the large scale information from GCM to scales, which are closer to the basin scale (25-50 km) but RCM results still show large bias in the magnitude and distribution of precipitation and to a lesser extent, temperature (Foley, 2010). RCM outputs are, therefore, not considered to be directly useful for assessing hydrological impacts at the regional and/or local scale. For this reason, RCM projections are bias corrected to obtain a reliable impression of the climate change and provide uncertainty information (Wetterhall *et al.*, 2012).

The World Climate Research Programme (WCRP) has recently launched a framework, called COordinated Regional climate Downscaling Experiment (CORDEX), to generate and evaluate fine-scale ensembles of regional climate projections for all continents globally (Giorgi *et al.*, 2009). CORDEX aims to improve confidence in regional trends of hydro-climatic key variables and increase robustness in hydrological long-term predictions. Among the several CORDEX domains, the South-Asia (SA) domain is a capacity building effort in the monsoon South-Asia to translate regional climate downscaled data into meaningful sustainable development information. CORDEX-SA was initiated in 2012 and the RCM outputs have only recently become available. However, climate projections still show bias in the magnitude and distribution, hence correction prior to impact assessment analysis is required (Chaturvedi *et al.*, 2012).

In this paper, we quantify the possible impacts on water availability in the Luni region, India, including the uncertainty of CORDEX-SA climate projections. Three projections using emission scenarios RCP2.6, RCP4.5 and RCP8.5 are examined to provide information on the uncertainty in the climate projections. The state of the art bias-correction method Distribution Based Scaling (Yang *et al.*, 2010) was used to improve on relevant biases for hydrological impact modelling in the area. Finally, the bias-corrected CORDEX-SA projections were introduced into the HYPE (HYdrological Predictions for the Environment) hydrological model to assess the impact of climate change on water over the Luni region. Section 2 introduces the study area, whereas the hydrological model and methodology are presented in Section 3. Section 4 presents the results of climate change impacts, followed by Conclusions and Discussion in Section 5.

2. Study region

The State of Rajasthan is situated in the western part of India, faces severe water scarcity, has low rainfall, and is classified as an arid/semi-arid region. Rajasthan is the largest state in India, covering 10.5% of the country's geographical area, but it shares only 1.15% of the country's water resources; the annual per capita water availability during 2001 was only 840 m^3 against the national average of 1140 m^3. Low and erratic rainfall, predominately deep dry sandy soil terrain, totally absent or irregular natural drainage in most parts, very deep and saline groundwater, very high evaporative conditions and frequent dust storms make the region vulnerable in all respects. In addition, the state encompasses a huge area of the Thar Desert. As a result, there are very few rivers in the western part of the state. The Luni River is one of the three major rivers flowing through Rajasthan and forms the only integrated drainage basin (34866 km^2) in northwest arid India (Figure 1). Annual precipitation in the Luni basin is highly variable, ranging from 600 mm in the southeast to 300 mm in the northwest; 93% of which is received during the monsoon months of June to September. The coefficient of variation ranges between 49 and 124%. Mean pan evaporation is 2640 mm/year, exceeding precipitation several times, so that streamflow is zero or near zero for much of the time. The Luni River is an ephemeral flow system,

conveying runoff only in direct response to the torrential monsoon rainfall (Sharma & Vangani, 1982); it is hence subject to extreme variability from year to year between zero flow and up to a daily maximum of 13920 m^3/s ($2409x10^6$ m^3, the highest volume with a 100 years return period).

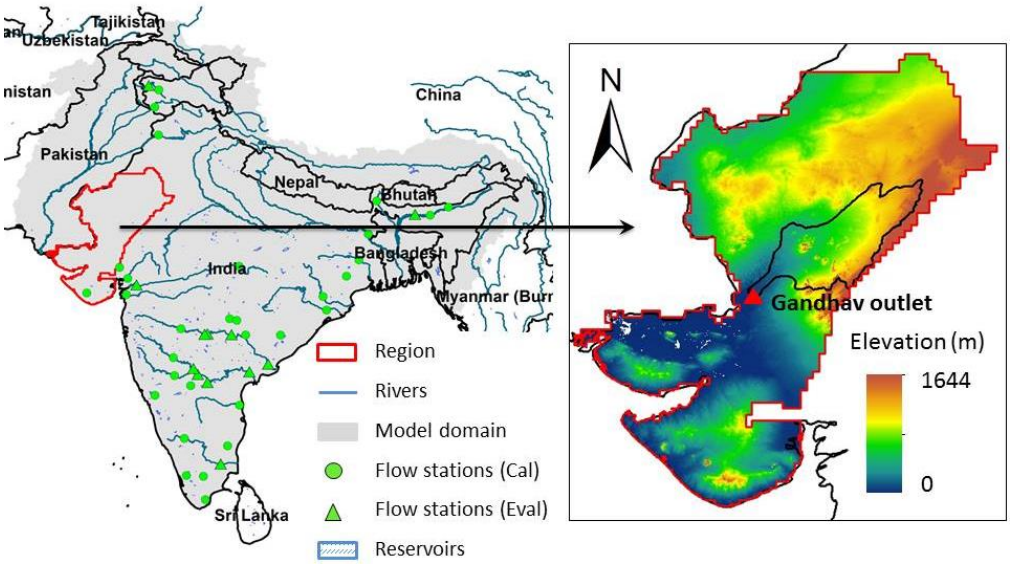

Figure 1. The study region (the Luni River basin is defined within the black border line)

3. Material and methods

3.1. Meteorological data – Reference period

Daily precipitation inputs for the period 1971-2005 were obtained from the Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) project (Yatagai *et al.*, 2009, 2012) at 0.25° resolution. Similarly, AphroTEMP (Yasutomi *et al.*, 2011) provided daily temperature inputs for the same period at 0.5° resolution. APHRODITE and AphroTEMP are the only long-term continental-scale datasets that contain a dense network of daily data for Asia including the Himalayas. Therefore, the datasets have contributed to studies including, among others, water resources, climate change analysis, and statistical downscaling. In this study, as a reference period, we have chosen 30 years from 1976 to 2005. The APHRODITE data set fully covers this reference period and the period does not overlap with the projection period of the climate models that starts in 2006.

3.2. Climate scenarios

Our ensemble of three climatic projections consists of modelling chains that use the same GCM (EC-EARTH; Hazeleger *et al.*, 2012) and RCM (RCA4; Samuelsson *et al.*, 2011), but three different representative concentration pathways, RCP (see Table 1). RCPs are named after a possible range of radiative forcing values in the year 2100 (+2.6, +4.5, and +8.5 W/m^2, respectively; Moss *et al.*, 2010). Previous research (e.g., Hawkins & Sutton, 2009) has shown that towards the end of the 21st century, the emission scenarios (here RCPs) are the dominant source of uncertainty in climate projections; hence, our focus is on addressing only this source of uncertainty. The RCM projections (mean daily precipitation and temperature) were bias corrected against the APHRODITE and AphroTEMP datasets using the Distribution Based Scaling, DBS, statistical method(Yang *et al.*, 2010) to obtain a reliable impression of the climate change. In brief, DBS aims to match the quantile distribution of bias-corrected data (precipitation and temperature) to the one of the reference data. For precipitation, a two-step procedure is applied: 1) correction of the wet-day frequency by applying a wet-day threshold or by adding wet-days to pre-existing wet-spells for the case of too many or too few wet-days, respectively; 2)

quantile-mapping of the precipitation data using a double gamma distribution to represent the normal and extreme precipitation range more accurately. The bias-corrected projections are further introduced into the hydrological model for the assessment of climate change impacts on water resources.

Table 1. The three CORDEX-SA climate projections

RCP (W m^{-2})	GCM	RCM	Reference data
2.6	EC-EARTH	RCA4 (0.44x0.44 deg)	APHRODITE (0.25x0.25 deg) AphroTEMP (0.5x0.5 deg)
4.5			
8.5			

3.3. The India-HYPE model application

The Hydrological Predictions for the Environment, HYPE, model (Lindström *et al.*, 2010) is a semi-distributed rainfall-runoff model capable of describing the hydrological processes at the basin scale. The model represents processes for snow accumulation and melting, evapotranspiration, soil moisture, discharge generation, groundwater recharge, and routing through rivers and lakes. HYPE simulates the water flow paths in soil which is divided into three layers with a fluctuating groundwater table. In addition, parameters are more linked to physiographical characteristics in the landscape, such as Hydrological Response Units (HRUs) linked to soil type and depths and vegetation. Elevation is used to get temperature variations within a sub-basin to influence the snow conditions. The model requires information on terrain, soil and land use, lakes and reservoirs and irrigation as input, which, in this application, has been obtained from the global sources.

Irrigation in HYPE is simulated based on crop water demands calculated either with the FAO-56 crop coefficient method (Allen *et al.*, 1998) or relative to a reference flooding level for submerged crops (e.g., rice). The demands are withdrawn from rivers, lakes, reservoirs, and/or groundwater within and/or external to the sub-basin where the demands originated. The demands are constrained by the water availability at these sources. After subtraction of conveyance losses, the withdrawn water is applied as additional infiltration to the irrigated soils from which the demands originated.

The HYPE model is setup for the entire Indian subcontinent (4.9 million km^2) for a resolution of 6010 sub-basins, i.e. in average 810 km^2 and is referred to as India-HYPE; however, herein we only present India-HYPE results for the Luni region which contains 417 sub-basins. The model (in this application) runs at a daily time step, however, due to the lack of discharge observations it was calibrated and validated (both in space and time) against monthly discharge observations from 42 GRDC (Global Runoff Data Centre) stations. For the Indian subcontinent, GRDC data are limited with monthly data for chosen river basins available for the years 1971 to 1979. Note that no discharge observations were available in the Luni region, thus we assume the parameter regionalisation to this ungauged region to be acceptable if the model performs adequately in the gauged basins over the entire model domain. The HYPE model was calibrated (Cal.) and validated (Val.) in a multi-basin approach (i.e., calculate the median performance from all selected stations); 30 and 12 stations were selected for model calibration and validation, respectively. The median Nash-Sutcliffe Efficiencies, NSE (Nash & Sutcliffe, 1970) and relative errors (RE) for the calibration and validation stations and periods are presented in Table 2.

Table 2. Median model performance for calibration and validation stations and periods

Space	Time	NSE	RE (%)
Cal. (30 stations)	Cal. (1971-1975)	0.74	-13.65
	Val. (1976-1979)	0.72	-11.86
Val. (12 stations)	Cal. (1971-1975)	0.66	6.95
	Val. (1976-1979)	0.10	16.81

Overall, the India-HYPE model achieved a good performance (best values for NSE and RE are 1.0 and 0.0, respectively), and is, therefore, considered adequate to describe the hydrological processes in the

domain.

3.4. Analysis of impacts

The study determines the present water availability in space and time using the reference datasets. The same framework is then used to predict the impact of climate change on the water resources with the assumption that the land use shall not change over time. A total of 124 years of hydrological simulations have been conducted for each climate scenario (1971-2099); however, the analysis is based on three 30-year periods: reference period (1976-2005), mid-century period (2021-2050), and end-century period (2070-2099).

In this paper, we assess the impact of climate change on: 1) the hydro-climatic components, i.e. precipitation (mm), actual evapotranspiration (mm), runoff (mm), soil moisture deficit (mm) and applied irrigation water to soil (Mm^3; defined as the water applied as additional infiltration to the irrigated soils from which the water demands originated); and 2) the hydrological signatures, i.e., flow duration curve and monthly average flow distribution.

The long-term variation in percentage in these basic hydro-climatic components for the investigated region is quantified. This change in the long-term average (%) between two periods due to climate is estimated for each sub-basin according to:

$$\text{Change}_i = \frac{X_{FP,i}-X_{RP,i}}{X_{RP,i}} \times 100$$

where *X* is the average value of the component over a selected period and sub-basin (*i*), *FP* is the future period (mid- or end-century) and *RP* is the reference period. Positive (negative) change indicates increase (decrease) from the average value in the reference period.

4. Results

4.1. Reference data analysis

To infer a quantitative understanding of the magnitude of the climate change impact on the hydro-climatic components, it is necessary to estimate the long-term average for the reference period (see Figure 2).

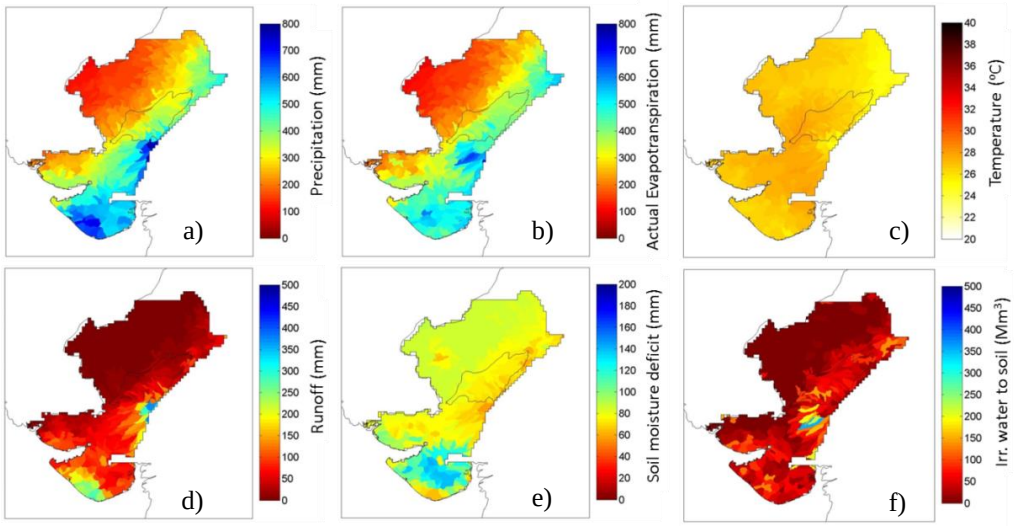

Figure 2. Region's annual averages (period 1976-2005) for the components: a) precipitation, b) actual evapotranspiration, c) temperature, d) runoff, e) soil moisture deficit and f) applied irrigation water to soil

The spatial pattern of precipitation and actual evapotranspiration seems similar; however, evapotranspiration is lower than precipitation by almost 20%, indicating that most precipitated water is evaporated back to the atmosphere. Note also the high temperatures in the region (average temperature varies between 25 and 30 °C). Generated runoff only varies between 0 and 90 mm/year in the region. In particular, the Luni basin generates 86 mm of mean annual runoff (mainly from the eastern region), whereas no runoff is generated in the north-western part of the region, i.e., the Thar Desert. The soil moisture deficit is between 60 and 120 mm/year and increases in the Thar Desert and the southern region; note the presence of a wetland covering this exact southern region. Finally, applied irrigation water to soil is close to 40 Mm^3 with some small variability in the region.

4.2. Impact of climate change on hydro-climatic components

Change in precipitation seems to be subject to the climate scenario and period of investigation (Figure 3). Overall, change varies between -20 and +20% over the region. A mixed spatial pattern of positive and negative changes in precipitation is present in the mid-century; however, the change becomes uniform over the region at the end-century, with RCP2.6 scenario predicting a decrease of precipitation (mainly in the northwest arid zone) whilst the other two scenarios predicting an increase of precipitation. Additional analysis (not presented here) showed that the inter-annual variability of the precipitation, described by the coefficient of variation (CV), is on the average close to 50% and gets larger in the western part. Moreover, the inter-annual variability gets larger in time indicating the presence of years with “extreme” climatic conditions.

All scenarios show a consistent increase in temperature both in space and time (see Figure 4). In the mid-century the change can reach about +5%, whereas only small spatial variability in the change is observed. However, the change is spatially homogeneous with values reaching up to 15% (almost 4.5 °C increase) for scenario RCP8.5.

Similarly to precipitation, the impact on evapotranspiration is different according to the RCP scenario (Figure 5). Overall, change in evapotranspiration varies between -20 and +20%, with the spatial variability becoming more uniform, and the change being more pronounced, in the end-century. Evapotranspiration is consistently reduced over the region under RCP2.6, and increased under RCP4.5 and RCP8.5 (in all scenarios, the impact over the Luni basin seems to be uniform). In addition, high inter-annual variability (i.e., 60%) is observed at the arid zone of the region.

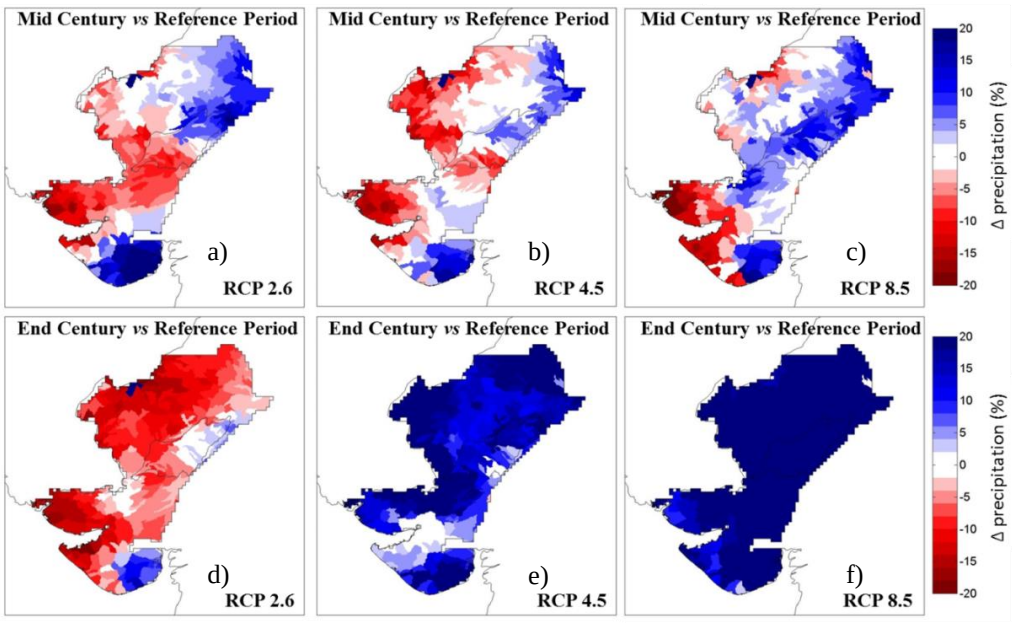

Figure 3. Relative change in precipitation under different climate scenario and period (a-c and d-f for mid- and end-century, respectively)

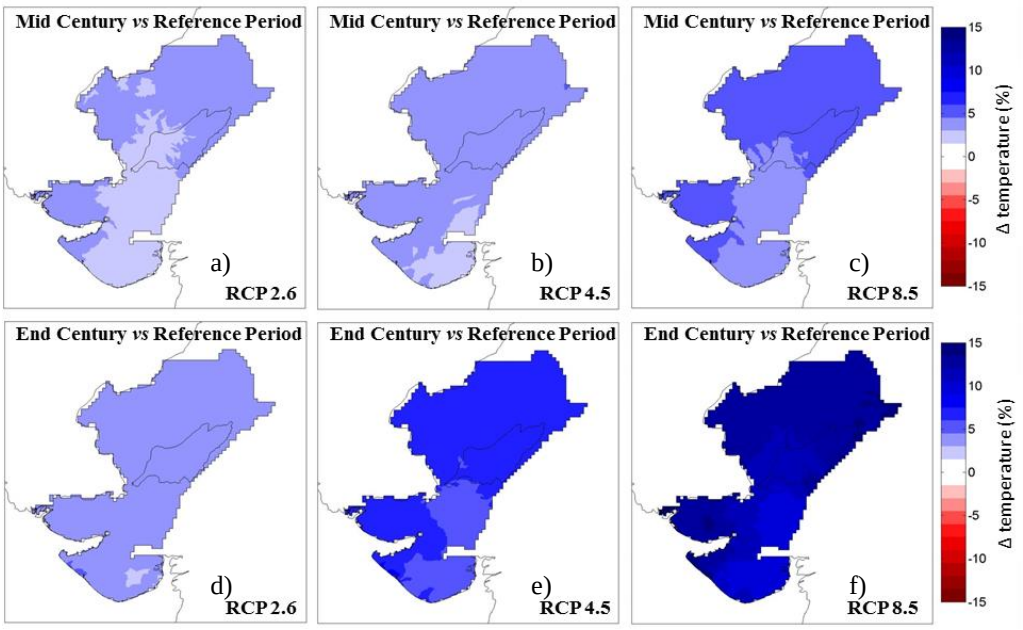

Figure 4. Relative change in temperature under different climate scenario and period (a-c and d-f for mid- and end-century, respectively)

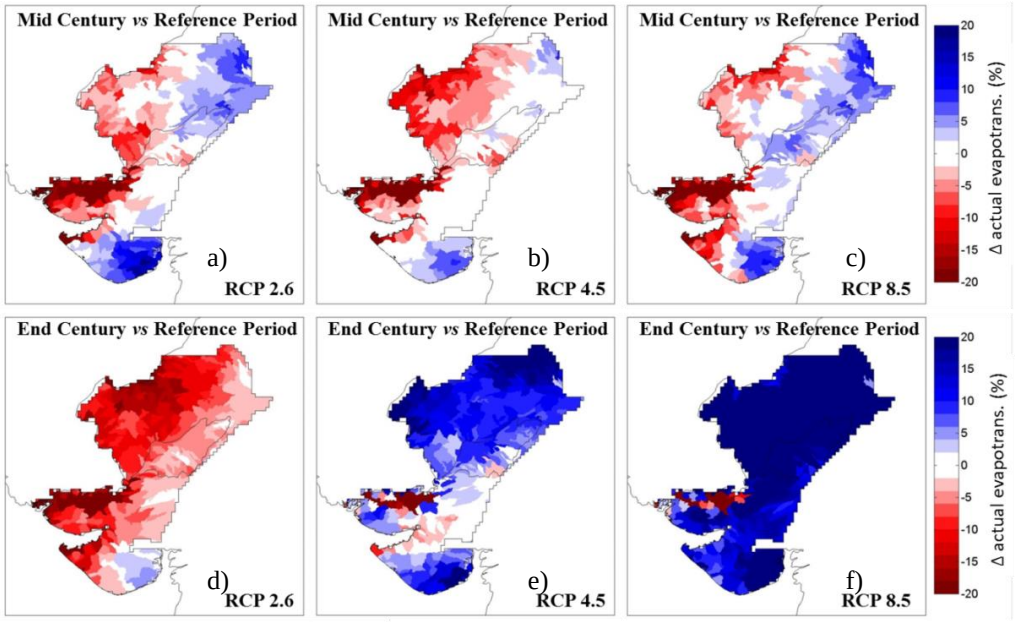

Figure 5. Relative change in actual evapotranspiration under different climate scenario and period (a-c and d-f for mid- and end-century, respectively)

The runoff response is dependent upon a combination of factors, such as weather conditions, terrain, soil and land use. Results, therefore, show that despite the decrease in precipitation from the reference to the future period, runoff is increased in some parts of the region (see Figure 6). Runoff showed higher relative change (between -40 and +40%) compared to precipitation and evapotranspiration. Although runoff in the Luni basin is reduced under RCP2.6 scenario, the other scenarios show a consistent increase during both mid- and end-century. The inter-annual variability was very strong (CV ≈ 100%), indicating changes in the annual flow magnitudes.

Results of climate change impact on soil moisture deficit indicate only a small alternation to the long-term average. Figure 7 shows that this change varies between -5 and +3%. However, this relatively small

change might have an impact on other sectors, i.e., agriculture, due to decrease of the groundwater table. Also note that this change is constant in time; CV is between 0 and 15%. In particular, the Luni basin seems to only be affected during the end-century for RCP2.6 and RCP8.5 scenarios, yet the impact between scenarios is different. Finally, consistent increase in the applied irrigation water to soil due to climate change is observed for all scenarios and periods (Figure 8). Overall, around 20% increase in applied irrigation water to soil is predicted at the end-century for RCP8.5 scenario, particularly in the Luni basin area.

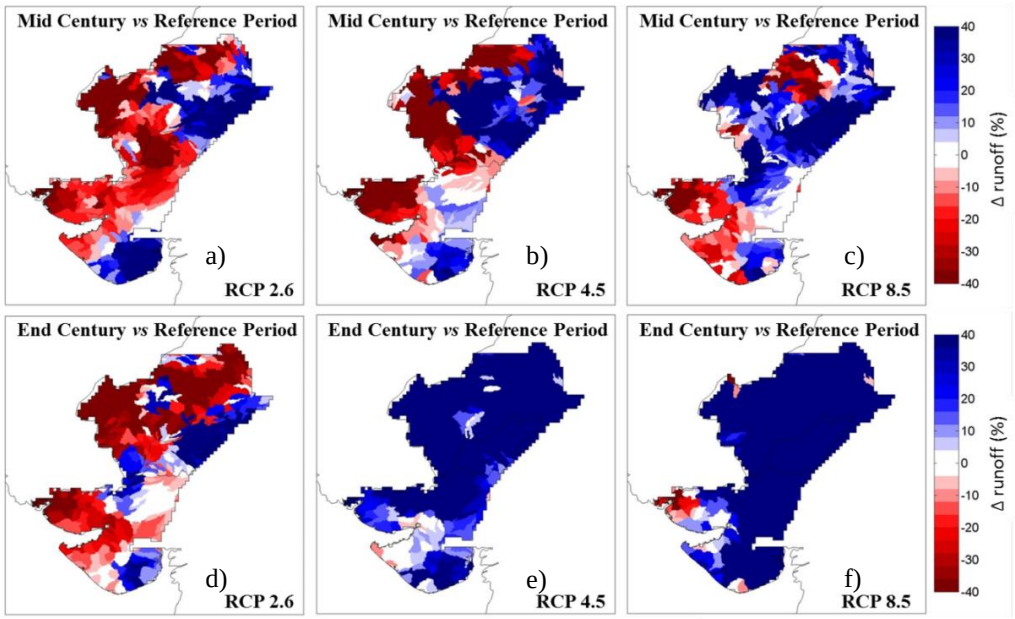

Figure 6. Relative change in specific runoff under different climate scenario and period (a-c and d-f for mid- and end-century, respectively).

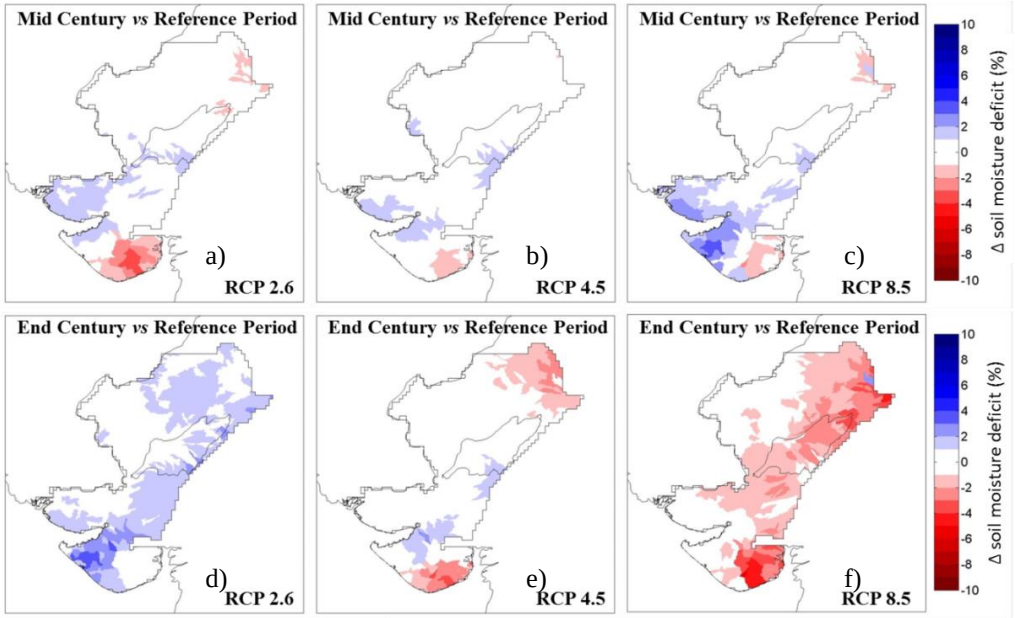

Figure 7. Relative change in soil moisture deficit under different climate scenario and period (a-c and d-f for mid- and end-century, respectively)

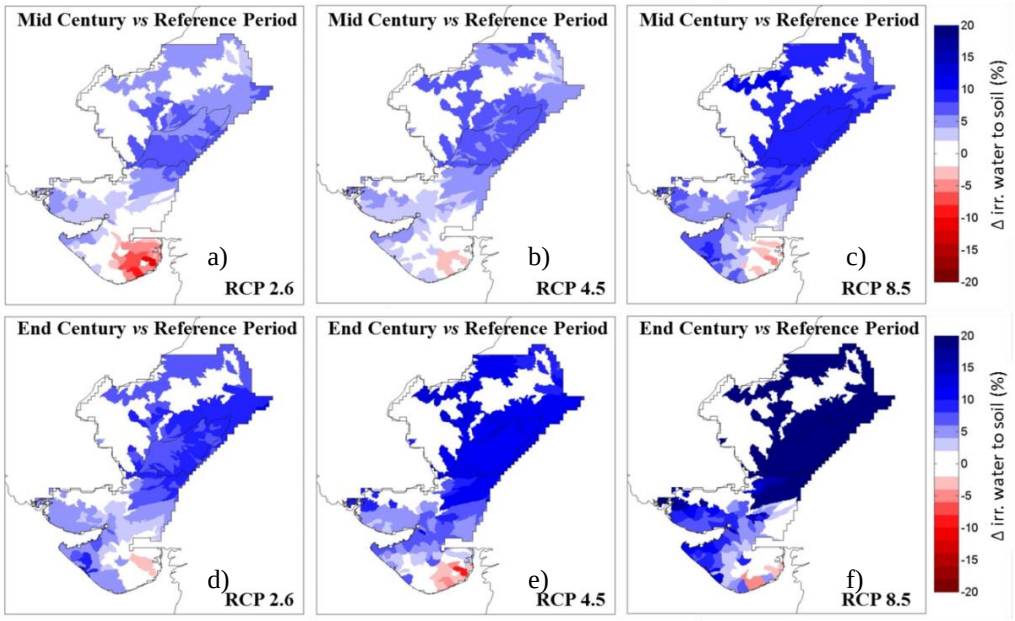

Figure 8. Relative change in applied irrigation water to soil under different climate scenario and period (a-c and d-f for mid- and end-century, respectively)

4.3. Impact on hydrological signatures

We next evaluate the impact of climate change on flow characteristics of the Luni river (at the Gandhavoutlet; see Figure 1), i.e., the flow duration curve (FDC) and seasonality, described by the mean monthly flow distribution. Figure 9 presents the FDCs for each RCP scenario and period of investigation; FDC for the reference period is also given to assist understanding of the change. Simulated flows seem to have similar distribution during the mid-century, i.e., slope of medium flows (medium flows are considered the values between the 20 and 60% probability of exceedance); however, there is an increase of the high flows (<2% probability of exceedance). The impact of climate change on the FDC is more pronounced during the end-century. In particular, the magnitude of medium and high flows is increased under RCP4.5 and RCP8.5 scenarios. Additionally, a change in the flow distribution is observed for RCP8.5, meaning that the duration of dry periods will decrease.

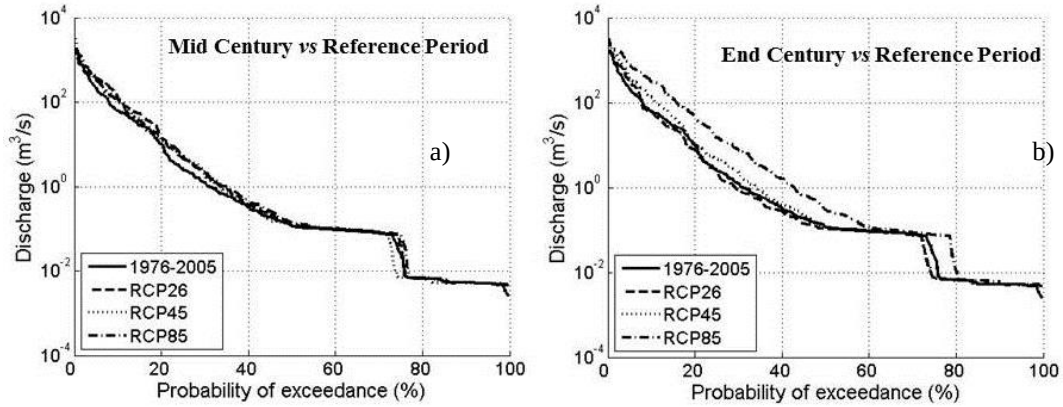

Figure 9. FDCs of the Luni basin (Gandhav outlet) for different climate scenario and period: a) mid-century (2021-2050), and b) end-century (2070-2099)

Finally, the monthly flow averages are substantially affected due to climate change. Figure 10 shows that the monthly highest flow can increase by almost 100% for RCP4.5 and RCP8.5 scenarios in the mid-century. This increase is even more pronounced in the end-century. However, it is important to note

that the peak of the mean monthly hydrograph is only slightly increased for RCP2.6 in both mid- and end-century. In addition, despite the change in the shape of the monthly hydrograph, a change in seasonality is observed during the mid-century. The highest monthly flow under all scenarios occurs in August compared to the highest monthly flow in the reference period that occurs in September. This is important information for the operation of the reservoirs in the region.

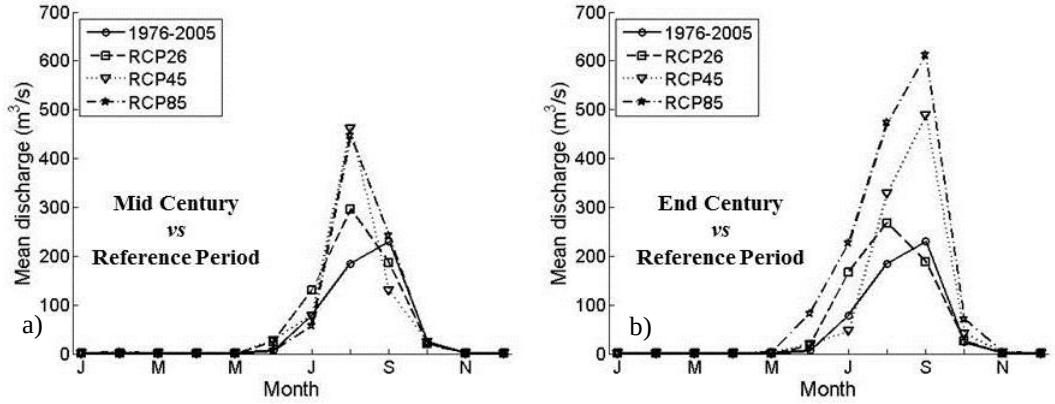

Figure 10. Mean monthly discharge in the Luni basin (Gandhav outlet) for different climate scenario and period: a) mid-century (2021-2050), and b) end-century (2070-2099)

5. Conclusions and discussion

Climate simulations from the CORDEX-SA initiative for three emission scenarios (RCP2.6, RCP4.5 and RCP8.5) are used to assess the hydrologic impacts of climate change in the Luni region. The India-HYPE model is forced with bias-corrected climate projections and changes are calculated for two future periods (mid- and end-century). Overall, the distribution of change varies considerably in space, whereas results are subject to the climate change scenario. In particular:

- Change in precipitation and evapotranspiration varies between -20 and +20%. RCP4.5 and RCP8.5 scenarios consistently predict increase in these fluxes (particularly in end-century), whereas RCP2.6 predicts reduction up to 10% for precipitation and up to 20% for evapotranspiration.
- Runoff is more sensitive to climate change (-40 to +40% change). Reduction in runoff during the end-century under RCP2.6 scenario is provided; however, runoff in the eastern Luni basin is increased. Significant increase is mainly predicted in end-century under RCP4.5 and RCP8.5.
- Change in soil moisture deficit ranges between -5 and +3%. The impacted area is increased towards the end-century.
- Consistent increase in time (up to 20%) in applied irrigation water to soil for all scenarios.
- The flow dynamics (magnitude and seasonality) are also impacted. Although the flow distribution is similar for all scenarios, there is a clear increasing trend in magnitude during mid- and end-century. The shape of the monthly hydrographs also substantially impacted.

Finally, it is important to note the limitations in this study. Firstly, we assume that land use shall not change in future and there are no man-made changes in the river system. Results are subject to the available data driving the hydrological model, whereas more recent and longer lengths of discharge series would improve the verifiability of the model results. Future investigations should include more projection ensembles, as in here we are only focused on different emission (here RCP) scenarios. It is also necessary to decompose the uncertainty of the results due to RCM climate projections, bias correction and impact modelling.

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References

Allen R.G., Pereira L.S., Raes D. and Smith M. (1998) Crop evapotranspiration (Guidelines for computing crop water requirements). *FAO, Rome*, 300. doi:10.1016/j.eja.2010.12.001.

Chaturvedi R., Joshi J., Jayaraman M., Bala G. and Ravindranath N. (2012), Multi-model climate change projections for India under representative concentration pathways, *Curr. Sci.*, **103**(7), 1–12.

Foley A. (2010), Uncertainty in regional climate modelling: A review, *Prog. Phys. Geogr.*, **34**(5), 647–670. doi:10.1177/0309133310375654.

Fowler H.J., Blenkinsop S. and Tebaldi C. (2007), Linking climate change modelling to impacts studies : recent advances in downscaling techniques for hydrological, *Int. J. Climatol.*, **27**, 1547–1578. doi:10.1002/joc.1556.

Giorgi F., Jones C. and Asrar G.R. (2009), Addressing climate information needs at the regional level: the CORDEX framework, *WMO Bull.*, **58**(3), 175–183.

GoI. (2004) India's Initial National Communication to the UNFCCC. Ministry of Environment and Forests. Government of India.

GoR. (2011) State Action Plan on Climate Change. Government of Rajasthan.

Gosain A., Rao S. and Arora A. (2011), Climate change impact assessment of water resources of India, *Curr. Sci.*, **101**(3), 356–371.

Hawkins E. and Sutton R. (2009), The potential to narrow uncertainty in regional climate predictions, *Bull. Am. Meteorol. Soc.*, **90**(8), 1095–1107. doi:10.1175/2009BAMS2607.1.

Hazeleger W., Wang X., Severijns C., Ştefănescu S., Bintanja R., Sterl A., Wyser K., Semmler T., Yang S., van den Hurk B., van Noije T., van der Linden E. and van der Wiel K. (2012), EC-Earth V2.2: description and validation of a new seamless earth system prediction model, *Clim. Dyn.*, **39**, 2611–2629. doi:10.1007/s00382-011-1228-5.

Lindström G., Pers C., Rosberg J., Strömqvist J. and Arheimer B. (2010), Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales, *Hydrol. Res.*, **41**(3-4), 295–319. doi:10.2166/nh.2010.007.

Moss R.H., Edmonds J.A., Hibbard K.A., Manning M.R., Rose S.K., van Vuuren D.P., Carter T.R., Emori S., Kainuma M., Kram T., Meehl G.A., Mitchell J.F.B., Nakicenovic N., Riahi K., Smith S.J., Stouffer R.J., Thomson A.M., Weyant J.P. and Wilbanks T.J. (2010), The next generation of scenarios for climate change research and assessment, *Nature*, **463**, 747–756.

Nash J.E. and Sutcliffe J.V. (1970), River flow forecasting through conceptual models, *J. Hydrol.*, **10**, 282–290.

Pechlivanidis I., Jackson B., McIntyre N. and Wheater H.S. (2011), Catchment scale hydrological modelling: A review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications, *Glob. NEST*, **13**(3), 193–214.

Raje D., Priya P. and Krishnan R. (2014), Macroscale hydrological modelling approach for study of large scale hydrologic impacts under climate change in Indian river basins, *Hydrol. Process.*, **28**(4), 1874–1889. doi:10.1002/hyp.9731.

Samuelsson P., Collin G.J., Willén U., Ullerstig A., Gollvik S., Hansson U., Jansson C., Kjellström E. Nikulin G. and Wyser K. (2011), The Rossby Centre Regional Climate model RCA3: model description and performance, *Tellus*, **63A**, 4–23. doi:10.1111/j.1600-0870.2010.00478.x.

Sharma K.D. and Vangani N.S. (1982), Flash flood of July 1979 in the Luni basin—a rare event in the Indian desert, *Hydrol. Sci. J.*, **27**(3), 385–397.

Wetterhall F., Pappenberger F., He Y., Freer J. and Cloke H.L. (2012), Conditioning model output statistics of regional climate model precipitation on circulation patterns, *Nonlinear Process. Geophys.*, **19**, 623–633. doi:10.5194/npg-19-623-2012.

Yang W., Andréasson J., Graham P.L., Olsson J., Rosberg J. and Wetterhall F. (2010), Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies, *Hydrol. Res.*, **41**(3-4), 211. doi:10.2166/nh.2010.004.

Yasutomi N., Hamada A. and Yatagai A. (2011), Development of a long-term daily gridded temperature dataset and its application to rain/snow discrimination of daily precipitation, *Glob. Environ. Res.*, **3**, 165–172.

Yatagai A., Arakawa O. and Kamiguchi K. (2009), A 44-year daily gridded precipitation dataset for Asia based on a dense network of rain gauges, *Sola*, **5**, 137–140. doi:10.2151/sola.2009–035.

Yatagai A., Kamiguchi K., Arakawa O., Hamada A., Yasutomi N. and Kitoh A. (2012), APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, *Bull. Am. Meteorol. Soc.*, **93**(9), 1401–1415. doi:10.1175/BAMS-D-11-00122.1.